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Technical Report

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by

F. C. Bell

Prepared for

Bureau of Land Management
U. S. Department of the Interior
as one of the reports
on investigations conducted under
Contract No. 14-11-0008-0590-62

Colorado State University
Civil Engineering Department
Fort Collins, Colorado
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EXTREME RAINFALL OF SHORT DURATION *

by F. C. Bell[1]

SYNOPSIS

Estimates of extreme rainfall of short duration are extensively used by engineers throughout the world but are generally the most unsatisfactory section of the available rainfall data. Local convective storm cells are largely responsible for these extreme values, particularly when the return periods exceed 10 years. The consistent physical characteristics of the cells appear to be reflected in surprisingly consistent relationships between the rainfall depths which are shown by expressing the depths as ratios to the 10 year 1 hour value.

These ratios vary with the duration and return period but are essentially independent of the rainfall magnitude and geographical location. The values derived for U.S.A. are also valid in other parts of the world. The estimated ratios for very extreme events are further verified by a modified station-year analysis, using the recorded maximum 1 hour values at a number of United States stations.

The results of the study may be generalized and combined into a single duration-frequency function for durations up to 2 hours and return periods up to 100 years. The function should be particularly useful for estimates in regions or countries with limited data.

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*Submitted in April 1967 to ASCE for possible publication in the Journal of the Hydraulics Division.

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[1] Visiting Professor, Department of Civil Engineering, Colorado State University (on leave from University of New South Wales, Australia).

INTRODUCTION

The efficient planning of many engineering works requires data on the frequency of extreme rainfall of short duration, i.e., from about five minutes up to several hours. This data is deficient throughout the world except for the relatively few localities where recording precipitation gages have been operating for long periods. During the past few years there have been some excellent studies of extreme rainfall and its characteristics in the United States[2, 3] but these have tended to emphasise the longer durations and do not show clearly the distinctive characteristics of short duration rainfall.

The data situation in the United States is relatively good and it can provide information that may be usefully applied in other countries. This has been demonstrated by Hershfield, Weiss and Wilson[4] and Reich[5] who have estimated rainfall frequencies in Africa with the aid of empirical relationships derived from U. S. data. In these studies the basic measure of short duration rainfall is the "2 year 1 hour" value which is the maximum depth in 1 hour with an average return period of 2 years (the "partial" or "exceedance"

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2. Hershfield, D. M., Extreme Rainfall Relationships. Journal of the Hydraulics Division, ASCE, Vol. 88, No. HY 6, Proc. Paper 3319, November 1962, pp. 73-92.

3. Hershfield, D. M., Rainfall Frequency Atlas of the United States. Weather Bureau Tech. Paper No. 40, 1961.

4. Hershfield, D. M., L. L. Weiss and W. T. Wilson, Synthesis of Rainfall-Intensity-Frequency Regime. Journal of the Hydraulics Division, ASCE, Vol. 81, No. HY 4, Proc. Paper 774, July 1955, pp. 1-6.

5. Reich, B. M., Short Duration Rainfall Intensity Estimates and Other Design Aids for Regions of Sparse Data. Journal of Hydrology, Vol. 1, No. 1, March 1963.

series is implied, as will be discussed later). The empirical relationships provide estimates of the 2 year 1 hour rainfall from readily available records such as the daily and mean annual precipitation. The same studies also suggest methods for obtaining extreme values with return periods greater than 2 years, but these are more appropriate for longer durations.

It appears preferable to regard short duration and long duration data as samples of different statistical populations that are only remotely related. Because of their special properties, short duration rainfall extremes are easier to estimate than is generally realized.

PHYSICAL ASPECTS

Characteristics of Local Convective Rainfall

Intense bursts of short duration rainfall occur either in brief, highly localized storms or within prolonged storms that cover extensive areas. In both cases each individual burst has a duration somewhat less than one hour and is associated with a local convective cell as described thoroughly elsewhere[6]. This type of rainfall will therefore be called "local convective" although the term "thunderstorm" is used frequently in the same context. The occurrence of thunder is usual but it is not an essential requirement.

Most local convective cells operate in small groups with various arrangements in time and space. Before some cells are dissipated, others are initiated in adjacent areas and it is not uncommon for chains of localized disturbances to proceed long distances in this manner.

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[6] U. S. Weather Bureau, The Thunderstorm. Report of the Thunderstorm Project, U. S. Government Printing Office, June 1949.

Each convective cell follows a resonably predictable sequence of events within a limited range of space dimensions and with a limited life span. These characteristics are governed chiefly by the physical properties of the atmosphere and are similar in most parts of the world. It is, therefore, reasonable to expect some general similarities in the depth-frequency patterns of the associated rainfall.

Indices of Local Convective Rainfall

Extreme rainfalls for durations of up to 2 hours are usually attributed to local convective activity but this may not be true for the full range of return periods in some areas. A study by Pilgrim in New South Wales[7] and brief examinations of U. S. records for coastal regions suggest that other types of storm activity can result in extreme values when the return period is less than 7 or 8 years. In these storms, high intensities occur continuously for a number of hours and the characteristic time-space concentrations of individual convective cells are not apparent.

In other studies, the basic measure or index value of short duration rainfall is either the 2 year or 1 year value.[4, 5, 8] If these are affected by several different storm types, they are unlikely to be consistently related to the more extreme values due primarily to local convective activity. In general, the more extreme values are

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[7] Pilgrim, D. H., Flood Producing Storms on Small Rural Catchments with Special Reference to New South Wales. Civil Engineering Transactions, Institution of Engineers, Australia, CE8 No. 1, April 1966.

[8] McIllwraith, J. F., Rainfall Intensity-Frequency Data for New South Wales. Journal of Institution of Engineers, Australia, Vol. 25, No. 7-8, July-August 1953.

of chief interest to engineers and it is therefore suggested that the index value should have a longer return period than 1 or 2 years. However, estimates for longer return periods are subject to greater sampling errors and it is necessary to compromise between the requirements of representativeness and accuracy. The 10 year value is suggested as a reasonable compromise.

Considering the above physical aspects it seems possible that any two places with the same 10 year 1 hour rainfall will have the same 1 hour frequency distribution for longer return periods. This hypothesis will be tested in later sections.

SPECIFICATION AND LIMITATIONS OF DATA

Annual and Partial Series

The term "annual series" is applied to an array of values consisting of the largest (or smallest) event from each year. This series is commonly used for analyses of extreme rainfall data because it satisfies the sampling conditions required by some statistical techniques, and also because the annual maxima are usually readily available.

However, the results of such analyses are often presented in terms of the "partial" or "exceedance" series which is more appropriate for practical applications of the data. This series is an array of all high values (above some arbitrary level), regardless of the year in which they occur. Several values occurring in the same year may be included if they are high enough, and the maxima from some years may be excluded if they are too low.

A particular value always has a larger return period with the annual series than with the partial series, the difference being about 0.5 years for return periods greater than 2 years.[9]

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[9] Dalrymple, T., Flood-Frequency Analyses. U. S. Geological Survey Water Supply Papers, 1543-A, 1960.

It is therefore a relatively simple matter to convert from one series to the other, although the difference is usually not important for the return periods of major interest.

In this paper, the partial series is implied unless otherwise indicated.

Presentation of Extreme Rainfall Data

Extreme rainfall data for an extensive area are difficult to present concisely when a large range of return periods and durations are of interest. The following methods are used:

(a) Series of isoline maps.[3]

(b) Depth-duration-frequency graphs for many points throughout the area of interest.[10]

(c) Empirical equations with a few maps or tables showing what parameters to use in the equations at various places.[11]

Methods (a) and (b) are convenient for the user and are generally about as accurate as the basic records allow. Method (c) is relatively inconvenient for the user as it involves extra calculations to produce the required information and, furthermore, the calculated values are often less accurate than for (a) and (b) because the fitting of the equations to the basic data may involve additional errors. Nevertheless, method (c) has been adopted in a number of cases because

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[10] U. S. Weather Bureau, Rainfall Intensity-Frequency Duration Curves for Selected Stations. U.S.W.B. Technical Paper No. 25, 1955.

[11] Institution of Engineers, Australia, Australian Rainfall and Runoff. First Report of the Stormwater Standards Committee, 1958.

it is the most concise way of presenting and specifying the large mass of data.

Inaccuracy of Extreme Rainfall Data

Estimates of extreme rainfall are never very accurate. According to Hershfield,[3] standard errors of 10 percent are the best that can be expected with the U. S. data and much higher errors are typical, especially for return periods of 50 to 100 years. The limited lengths of the sample records are a major source of uncertainty that may be expressed quantitatively by control curves or confidence limits about the frequency distribution.[12]

Figure 1 shows the 68 percent confidence limits for typical extreme rainfall values, assuming the Gumbel distribution.[13] These limits are for estimates of the partial series return period and indicate the values corresponding to various lengths of record. The figure suggests that the 10 year value is only slightly less accurate than the 2 year value when the record exceed 25 years in length.

DEPTH-DURATION RELATIONS

Empirical Equations

A general equation that has been widely used for expressing relationships between extreme rainfall and duration is:

$$p = \frac{A}{(t + b)^n} \tag{1}$$

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[12] Chow, V. T., Section 8-I on Frequency Analysis. Applied Hydrology, edited by V. T. Chow, McGraw-Hill, 1964.

[13] Gumbel, E. J., Statistics of Extremes. Columbia University Press, New York, 1960.

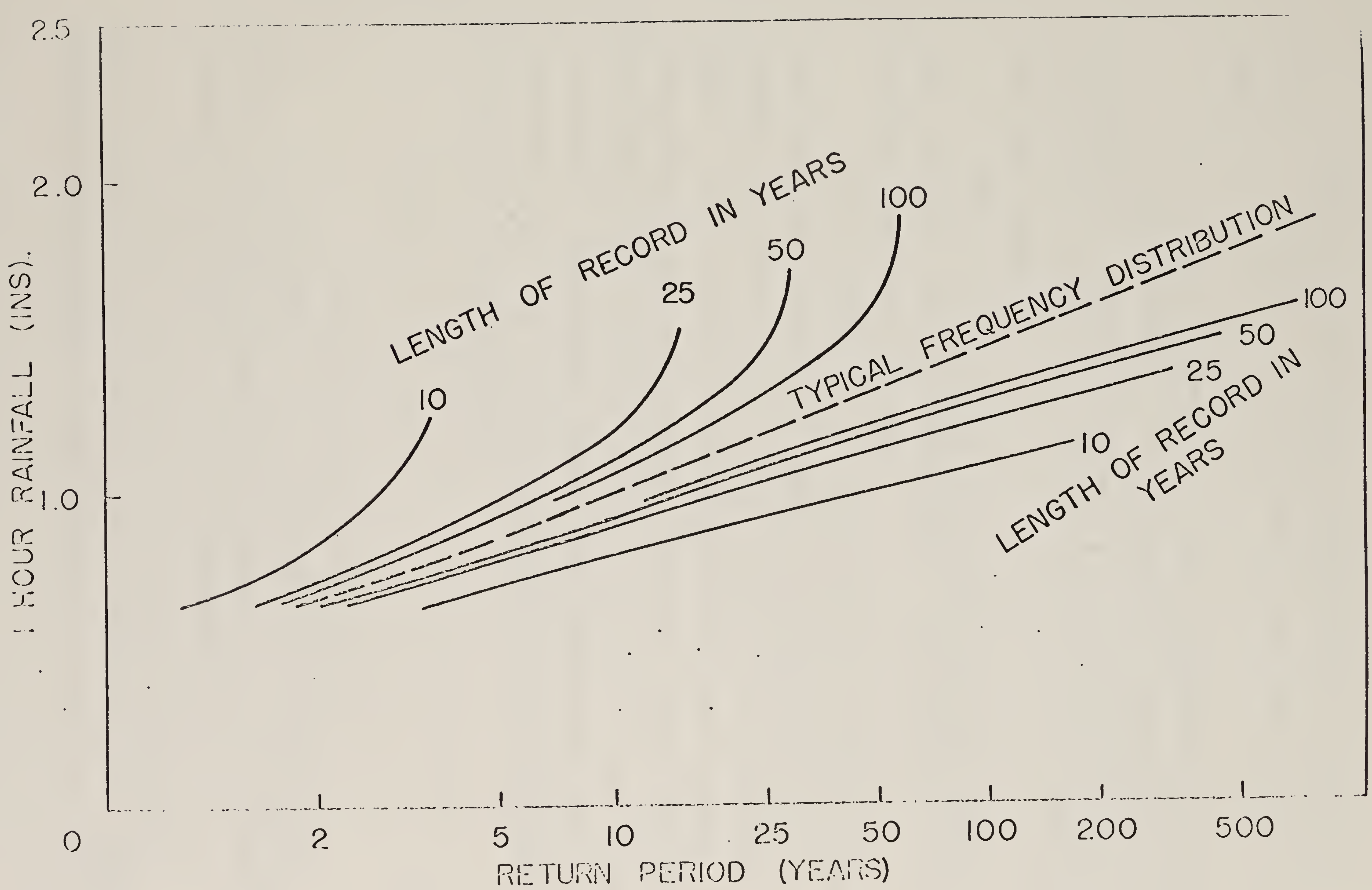

FIGURE 1 Effects of length of record on sampling errors. The 68% confidence limits are shown for a typical frequency distribution of 1 hour rainfall.

where p is the average rainfall intensity in mm/min. or ins/hr. for duration t in minutes and a fixed return period Y in years.

A, b and n depend on Y and the geographical location.

In Soviet Russia,[14] A represents the instantaneous rainfall intensity for a particular value of Y, b is assumed to equal 1 for the entire country and n varies from 0.50 to 0.67, depending only on the location.

Different values of these parameters have been adopted in other countries, such as Czechoslovakia[15] and Australia,[11] but the general approach is the same.

Similar equations were used in the U.S.A. several decades ago but they appear to have few applications today because more reliable values are obtained with less trouble from the published maps.[2] The U.S. Weather Bureau has also developed a simple interpolation diagram which enables reasonable rainfall estimates for any intermediate duration when the 1 hour and 24 hour values are known.[13] This diagram applies to the entire country and is very convenient to use. By elementary geometry it may be shown that it implies the following equation:

$$P_t = (1 - c)\,P_1 + cP_{24} \qquad (2)$$

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[14] Maksimov, V. A., An Outstanding Rainstorm in the Donbas. Soviet Hydrology: Selected Papers, No. 1, 1964, English translation, Published by American Geophysical Union.

[15] Trupl, Josef, Relationship between Intensities of Short Duration Rainfalls and Occurrence of Thunderstorms, Hydraulic Research Institute Report, Prague-Podbaba, Czechslovakia, 1959.

where P_t = Y year t hour rainfall.

P_1 = Y year 1 hour rainfall.

P_{24} = Y year 24 hour rainfall.

c = a constant that depends only on t.

It was found by Reich[5] that the U. S. values of c are valid in South Africa for durations longer than 6 hours but not for other durations. Similar conclusions have been made from preliminary analyses of Australian records.

Equation (2) enables separate treatments of 1 hour, 6 hour and other selected rainfall extremes. This approach seems more logical and less restricted than the approach implied by equation (1). The parameters of equation (1) are derived to give the best overall fit for the full range of durations but their values are unlikely to be the most suitable for a small part of the range such as the short durations.

Depth-Duration Ratios in U. S. A.

Separate analyses of short duration data have been made in U. S. A. by other investigators whose findings suggest the usefulness of expressing the t hour rainfall as a ratio to the 1 hour rainfall of the same return period. These "depth-duration ratios" have the following properties:

(a) they are independent of the return period

(b) they are independent of the magnitude of the rainfall

(c) a single ratio corresponds with each value of t and there is no significant variation over extensive areas.

The above properties are implied in analyses by Hathaway[16] and in the previously mentioned study by Hershfield, Weiss and Wilson.[4]

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[16] Hathaway, G. A., Military Airfields: Design of Drainage Facilities. Transactions ASCE, Vol. 110, Paper No. 2247, 1945 pp. 697-733.

U.S. Weather Bureau Technical Paper No. 40 also supports these ideas by indicating that the 5, 10, 15 and 30 minute rainfalls have ratios of 0.29, 0.45, 0.57 and 0.79 respectively to the 1 hour rainfall of the same return period.[3] The ratios apply to the entire U.S.A. with estimated "average errors" of 5 percent to 8 percent, most of which can be attributed to sampling (see Figure 1).

Because local convective activity has a major influence on extreme rainfalls up to several hours it is feasible to derive a depth-duration ratio for 2 hours. This has been done by the author from published records of the U.S. Weather Bureau,[10] using the 10 year values from the 157 stations with more than 40 years of data. The computed mean ratio is 1.24 which is represented graphically by a line through the plotted values in Figure 2. The standard deviation is .076, corresponding approximately with an average error of 6 percent.

Depth-Duration Ratios in Other Countries

It was suggested by Reich[5] that the U.S. depth-duration ratios may be valid throughout the world, after he found that the same values applied to South Africa. This hypothesis may be tested further with published Australian data, using all available stations with more than 30 years of records.[11, 17] Only 7 stations meet this requirement but they represent a reasonable range of climatic conditions, as shown in Figure 3.

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17. Fleming, P. M., Rainfall Intensity Relations in the Riverina. Paper presented to Division Meeting, Institution of Engineers, Australia, Wagga, New South Wales, 1964.

The calculated Australian ratios for three different return periods are summarized and compared with the U.S. ratios in Table 1. The sets of values are plotted in Figure 2 which shows no systematic deviations due to rainfall magnitude or return period.

Statistical tests of significance show that the calculated Australian ratios could represent random samples of the U.S. ratios with probabilities of .20 to .40 and the differences are therefore not significant.

It should be noted that an independent study of other shorter Australian records has been made by Stewart[18] who derived depth-duration ratios with 5 minutes as the basic value. When these are converted to an hourly basis, they agree almost exactly with the U.S. values.

Some idea may be gained of the ranges of depth-duration ratios implied by the empirical equation (1) used in Soviet Russia.[14] The t minute ratio may be examined by manipulating the equation as follows:

$$\text{Ratio} = \frac{At}{(t+1)^n} \Big/ \frac{60A}{61^n} = \frac{t}{60}\left(\frac{61}{t+1}\right)^n \qquad (3)$$

The maximum and minimum ratios occur respectively with the maximum and minimum values of n, i.e., 0.67 and 0.50. These limiting values have been calculated and listed in Table 2, together with the estimated ranges of U.S. values that may be expected due to sampling and other errors (one standard deviation above and below the mean).

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[18] Stewart, J., Rainfall Intensities in New South Wales. Soil Conservation Journal of N.S.W., October 1960.

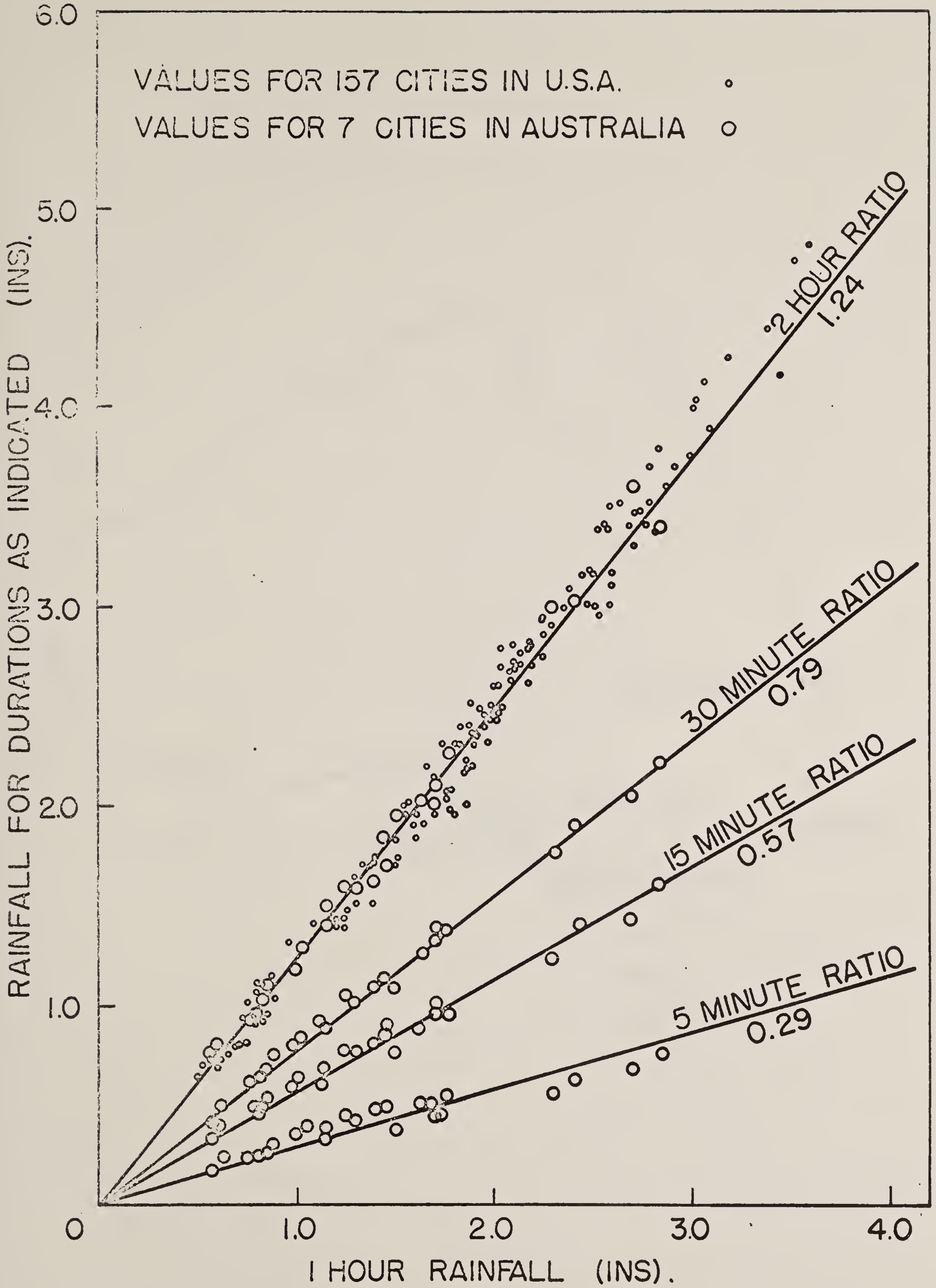

FIGURE 2 Comparison between depth-duration ratios for U. S. A. and Australia.

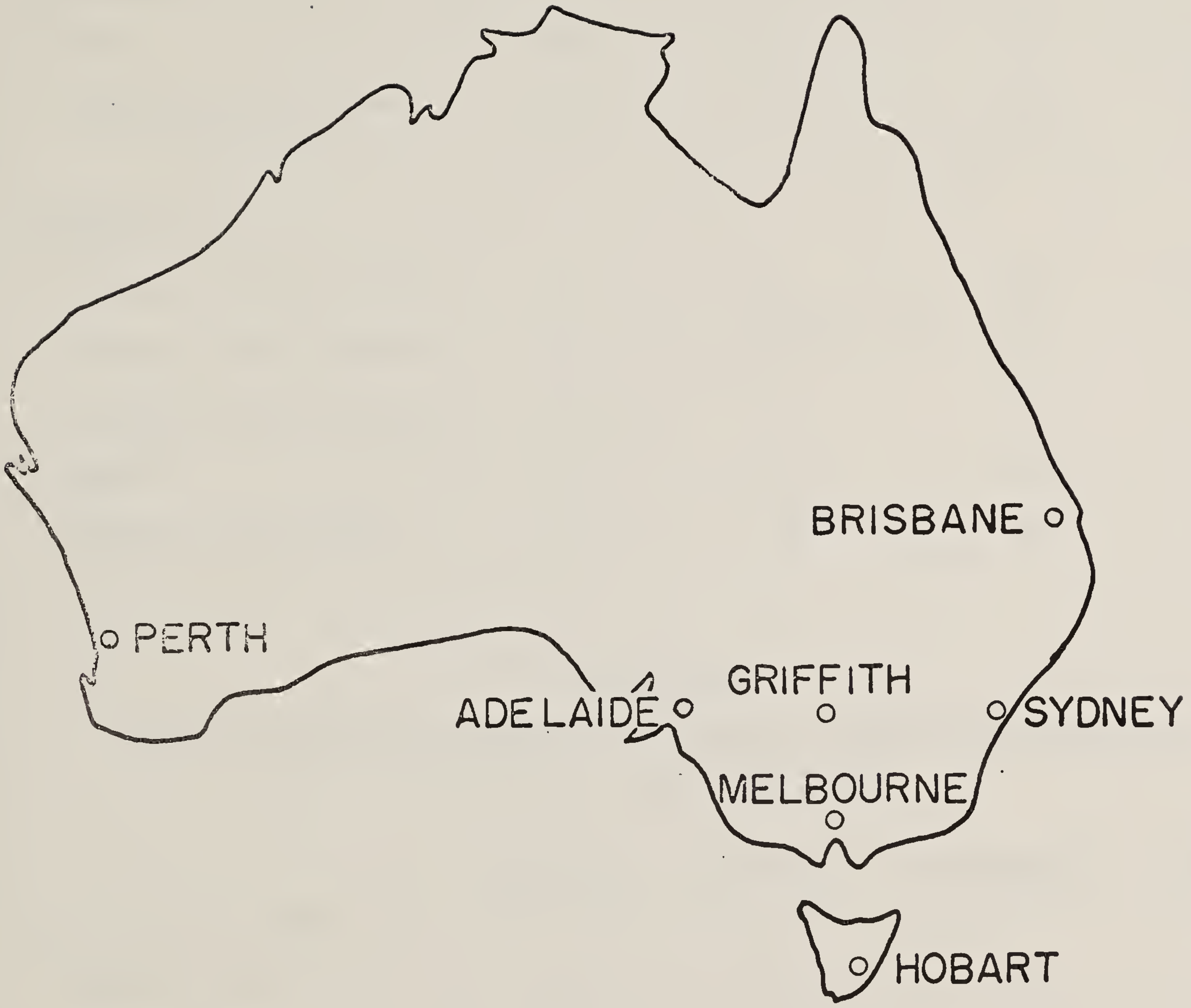

FIGURE 3 Recording precipitation stations in Australia with long records.

TABLE 1

COMPARISON BETWEEN DURATION RATIOS FOR U.S.A. AND AUSTRALIA

	5 minute	15minute	30 minute	2 hour
UNITED STATES				
Mean	.29	.57	.79	1.24
Standard Deviation (approx.)	.03	.04	.04	.07
AUSTRALIA				
2 year return period	.30	.57	.77	1.24
10 year return period	.31	.58	.78	1.25
25 year return period	.30	.58	.79	1.23
Mean	.30	.57	.78	1.24
Standard Deviation	.04	.04	.03	.06

TABLE 2

COMPARISON BETWEEN RANGES OF DURATION RATIOS IN U.S.A. AND U.S.S.R.

	5 minute	15 minute	30 minute	2 hour
UNITED STATES				
Upper value	.32	.61	.83	1.31
Lower value	.26	.53	.75	1.17
U.S.S.R.				
Maximum value	.37	.61	.87	1.40
Minimum value	.26	.49	.71	1.20

Although the comparison is between somewhat different statistics, Table 2 shows that the range of ratios used in U.S.S.R. is similar to the range of ratios expected in U.S.A. The U.S.S.R. values are supposed to vary systematically with the geographical location but the parameters expressing these characteristics are derived largely from long duration data and do not necessarily represent the short duration data very closely.

This preliminary analysis suggests that the U.S. depth-duration ratios could possibly apply to European conditions. More detailed investigations could not be made because the required data was not readily available.

DEPTH-FREQUENCY RELATIONS

Theoretical Frequency Distribution

It is often advantageous to assume specific mathematical forms of frequency distributions for hydrologic data, particularly when records are brief and extrapolations to long return periods are necessary. Mathematical forms are implied when the distributions are represented by straight lines through the plotted values of rainfall and return period on special graph paper such as log-normal, semi-log and "Gumbel" (extremal probability) paper. These, and the associated equations, are discussed in detail by Chow[12] who also shows how most of them may be interrelated and generalized.

The Gumbel distribution has some theoretical justification for describing extreme rainfall frequencies. It is actually the Fisher-Tippett Type I distribution derived originally for extreme maxima with no upper limit.[13] There is also a Fisher-Tippett Type III distribution for extreme maxima that have an upper limit and it would be more logical to use this if the concepts of absolute maximum

precipitation are accepted.[19] However, there is little merit in pursuing arguments on this matter when return periods of 100 years or less are of major interest because the calculated differences between the two distributions are usually smaller than the sampling errors and the Gumbel procedure has definite advantages of simplicity and convenience.

There are other assumptions inherent in the Gumbel procedure that may be violated by rainfall data. For example, the events for different return periods may be associated with different storm mechanisms (as discussed earlier) and are therefore not representative samples of the same population. Thus, the "true" frequency distribution at a particular place need not follow the Gumbel or any other specific mathematical form. In many cases the less extreme part of the distribution would be most accurately represented by a smooth, but otherwise unrestricted, curve drawn through the plotted points of a graph (despite the subjective elements of this procedure).

In some studies, it has been found useful to generalize rainfall distributions by means of "depth-frequency ratios" in which the denominators are either the 1 year or 2 year values, as discussed previously. These ratios show a large amount of variability and the suitability of the 10 year value as a denominator will therefore be examined in the next few sections.

Depth-Frequency Ratios in U.S.A.

In the derivation of the 2 hour depth-duration ratio, 157 U.S. stations with published records longer than 40 years were selected.

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[19] Gilman, C.S., Rainfall. Section 9 in Applied Hydrology by V. T. Chow, McGraw-Hill, 1964.

The 10 year 1 hour values of the same stations are shown plotted against the corresponding 1, 2, 5, 25, 50 and 100 year values in Figures 4 and 5. Considering the sampling errors involved, the plotted points show surprisingly small scatter, supporting the hypothesis that two places with the same 10 year 1 hour rainfall have the same frequency distributions for short duration rainfall of longer return periods.

The plotted points of Figures 4 and 5 also have distinct linear trends passing through the origin and the deviations increase in proportion to the rainfall, verifying that simple ratios are an appropriate means of generalizing the data.

The computed mean ratios to the 10 year value and the corresponding standard deviations are:

Return Period	Mean Ratio	Standard Deviation
1 year	.54	.05
2 year	.63	.05
5 year	.85	.03
25 year	1.17	.05
50 year	1.31	.06
100 year	1.46	.07

The above mean values are represented by the lines drawn through the plotted points in Figures 4 and 5. It may be seen that they apply satisfactorily to the full range of rainfalls for return periods of 2 to 100 years. With the 100 year return period, the mean ratio tends to be too high for high rainfall intensity regions and too low for low intensity regions. This does not appear to be important when the uncertainties of estimates for 100 year return periods are considered (see Figure 1).

Figure 6 indicates similar relationships with the 2 year rainfall as the denominator. The corresponding ratios for 25 and 100 year return periods are 1.87 and 2.32 respectively with standard

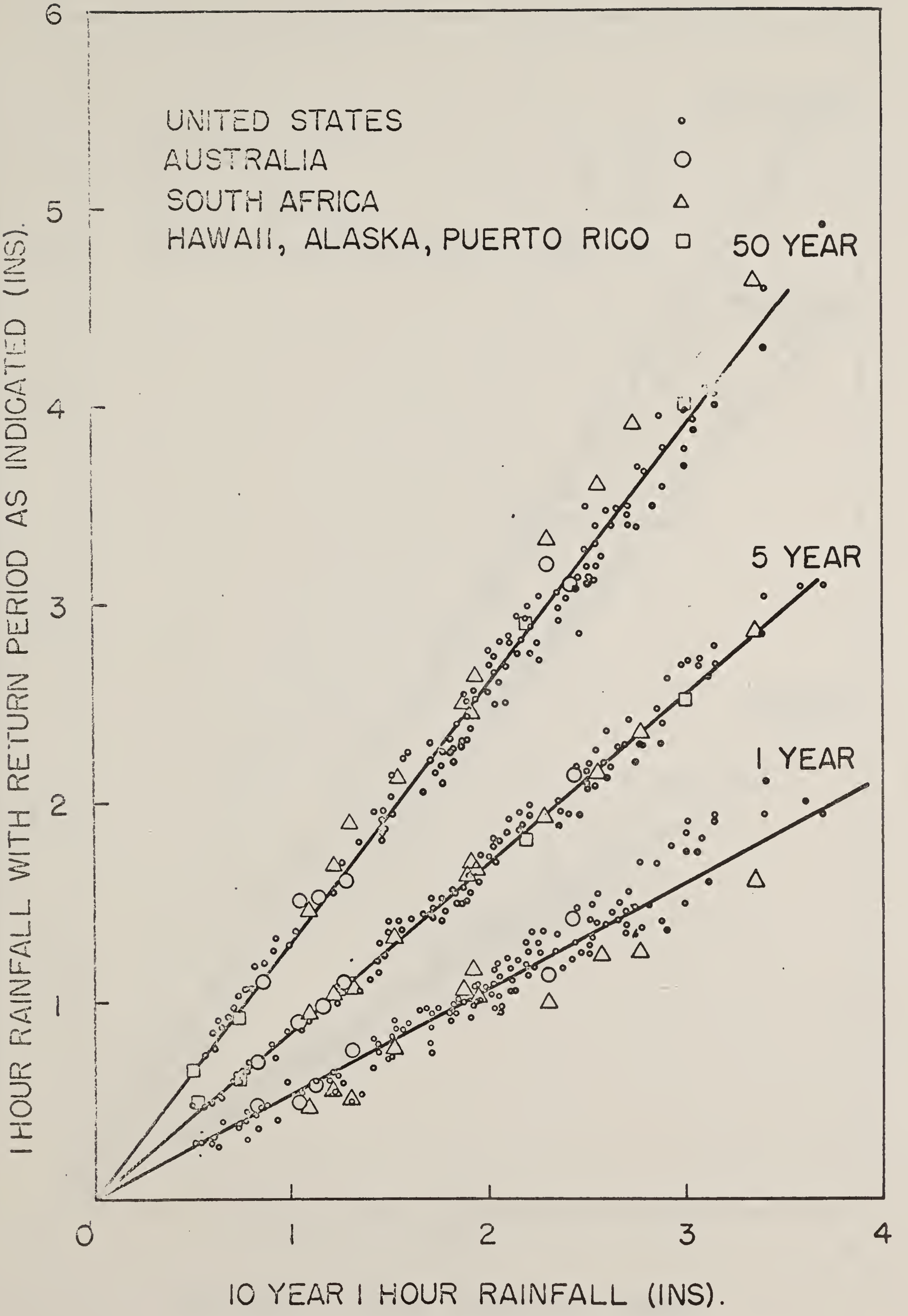

FIGURE 4 Derivation of 1 year, 5 year and 50 year depth-frequency ratios.

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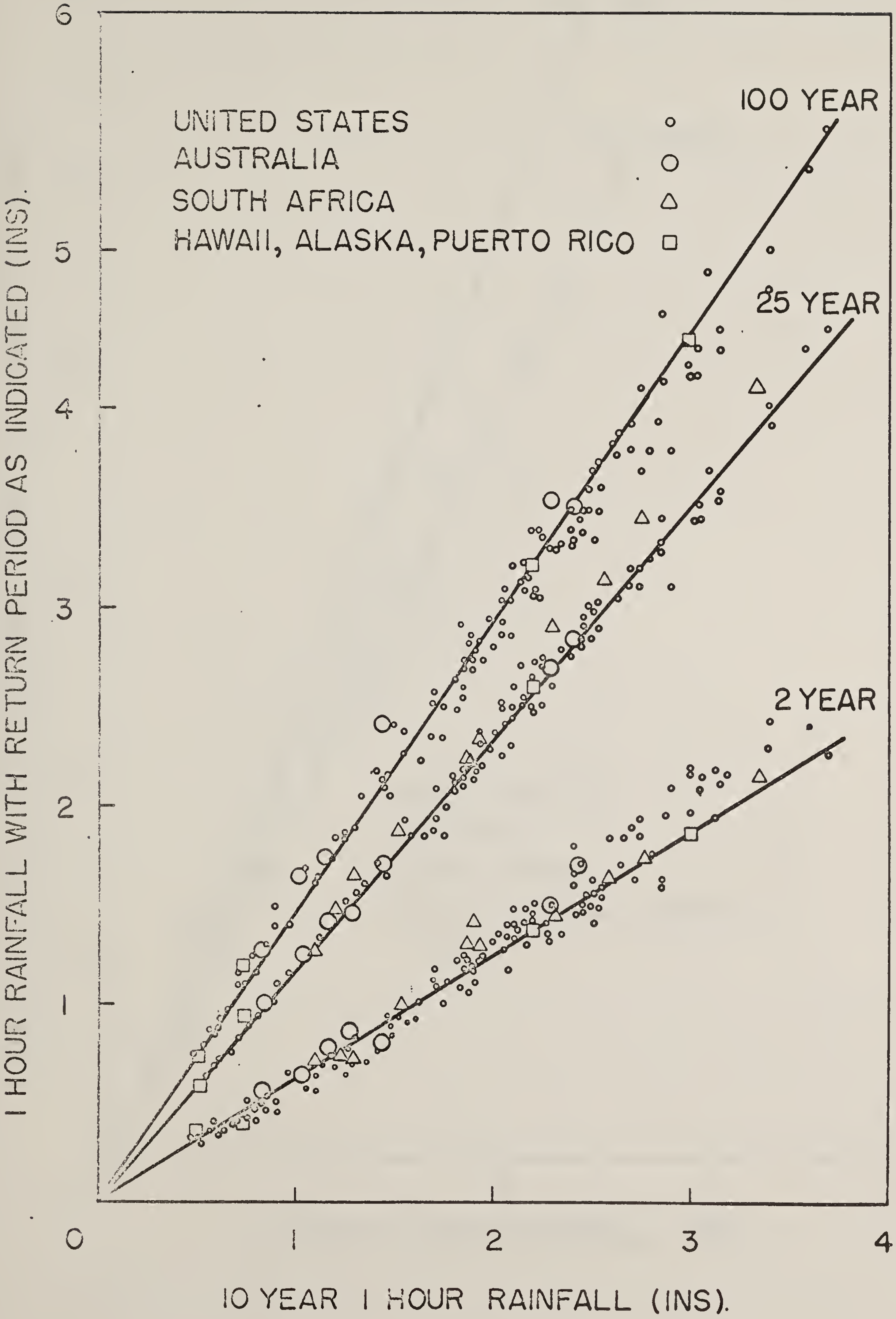

FIGURE 5 Derivation of 2 year, 25 year and 100 year depth-frequency ratios.

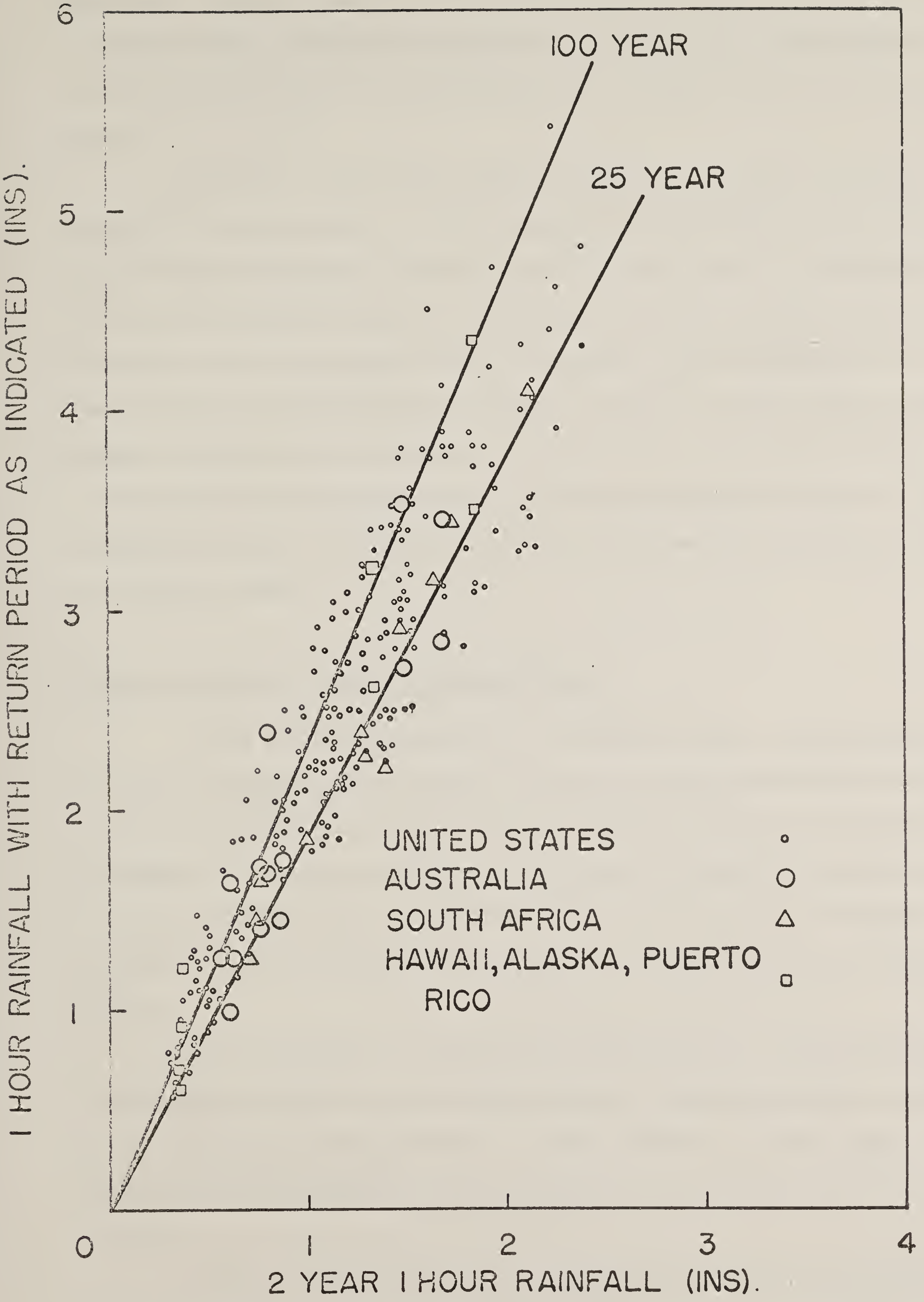

FIGURE 6 Depth-frequency ratios with 2 year value as denominator.

deviations of 0.20 and 0.35. The variability with the 2 year base is therefore larger than the variability with the 10 year base, and Figure 1 suggests that the difference would not generally be compensated for by the difference in sampling errors, unless the record is very short.

The U.S. individual station values for 50 and 100 years depend, to some extent, on the adoption of the Gumbel distribution in the original Weather Bureau study[10] and it may be thought that this factor partly accounts for the small scatter of values and consistency of the calculated ratios. However, the assumption of a general form of distribution does not, in itself, restrict the possible range of ratios for a particular return period, as may be easily demonstrated by drawing lines of different slopes on Gumbel or log probability paper. Further tests of the derived values of the ratios will now be made.

Depth-Frequency Ratios in Other Areas

Also plotted in Figures 4, 5 and 6 are the corresponding data for Australia, South Africa, Hawaii, Alaska and Puerto Rico, using all available stations with more than 20 years of records.[5, 10, 11] As some of the stations only just meet this criterion, the sampling errors are higher than those of the 157 U.S. values from longer records. This is reflected in the greater dispersion of the plotted points.

Nevertheless, it is apparent that the U.S. ratios would give reasonable estimates in most of the places represented and, furthermore, these estimates could possibly be more reliable for the longer return periods than those obtained by extrapolation from the brief individual records.

The records from the 7 Australian stations are all of moderate length (34 to 76 years) and may be used for independent derivations

of the depth-frequency ratios. Their calculated mean values and standard deviations are:

Return Period	Mean Ratio	Standard Deviation
1 year	.52	.05
2 year	.65	.05
5 year	.85	.05
25 year	1.18	.03
50 year	1.33	.06
100 year	1.50	.08

It may be readily shown that there is no significant statistical difference between the above Australian ratios and the previously derived U.S. ratios.

Other studies of Australian rainfall frequency relations have been made by Stewart[18] and McIllwraith.[8] Stewart proposed a frequency function of logarithmic form with parameters that vary geographically according to the mean annual dew point.

McIllwraith examined a large amount of data and concluded that the annual series of extreme rainfall have log normal distributions for all durations from 5 minutes to 3 days. He developed frequency functions expressed in terms of the standard deviation of the transformed series and a constant value of .18 was adopted for this throughout Australia for durations less than 2 hours. It may be shown that McIllwraith's function implies depth-frequency ratios of 0.66, 0.84, 1.20, 1.36 and 1.52 for return periods of 2, 5, 25, 50 and 100 years respectively with the 10 year value as the denominator. The agreement with the previously derived ratios is quite reasonable.

Very Extreme Rainfall

When high degrees of safety and return periods exceeding 100 years are involved, tha mathematical form of the frequency distribution becomes a more important issue. Under such

circumstances the concept of an absolute maximum value also has some practical significance and should not be dismissed because of the uncertainties involved in its estimation.

In general, the recorded rainfall values at any individual station do not contain sufficient information for reliable determinations of very extreme values but improved estimates are possible if additional information or knowledge can be introduced from other sources. Two possible ways of doing this are:

(a) The assumption of the Fisher-Tippett Type III distribution and the estimation of the asymptotic value (the absolute maximum) from largely independent meteorological information.

(b) An appropriate synthesis of the particular station record with data from other stations subject to similar influences. Examples of this are the "station-year" method[19] and regional frequency analyses.[9]

No attempts will be made in this paper to deal further with method (a) which is a controversial matter.

In the station-year method, it is assumed that the combined record of, say, 10 stations each with 20 years of data are equivalent to a 200 year record from a single station. It can be demonstrated that the assumption is valid if:

(a) The occurrence of any particular value has the same probability at all stations, i.e., a single frequency distribution is common to all stations. This is usually called "meteorological homogeneity."

(b) Values at different stations are statictically independent, i.e., each event only affects one station.

The station-year method has suffered considerable disrepute because the above requirements have been seriously violated in some of its past applications. This is unfortunate because it can be a

powerful analytical technique when efforts are made to ensure that the conditions are fulfilled.

The previous sections suggest that short duration data comply with requirement (a) if the depth-duration ratios are used instead of the actual values. Local convective rainfall is always concentrated in relatively small areas and stations more than 40 miles apart rarely experience an extreme event in the same storm, fulfilling requirement (b).

The station-year method is therefore suitable for statistically combining the extreme values at gages more than 40 miles apart when the recorded maxima are converted to depth-duration ratios with the 10 year value as denominator. An analysis of this type has been carried out for the recorded maximum hourly rainfalls in the regions of highest and lowest rainfall intensities of U.S.A., as shown in Figure 7. All stations with published data[20] and having more than 30 years of observations were selected, giving a combined record of 1,498 years in one region and 1,587 years in the other region.

The ratios of the recorded maxima at the above stations are ranked in Table 3, and the corresponding return periods are shown for both the "record series" and the partial series. The record series return periods were calculated by assuming that the values are from samples of equal length, i.e., the average record lengths of 56 and 59 years. These were converted to the partial series by using the principles mentioned previously.[9]

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20. U.S. Weather Bureau, Maximum Recorded United States Point Rainfall. U.S.W.B. Technical Paper No. 2, Revised 1963.

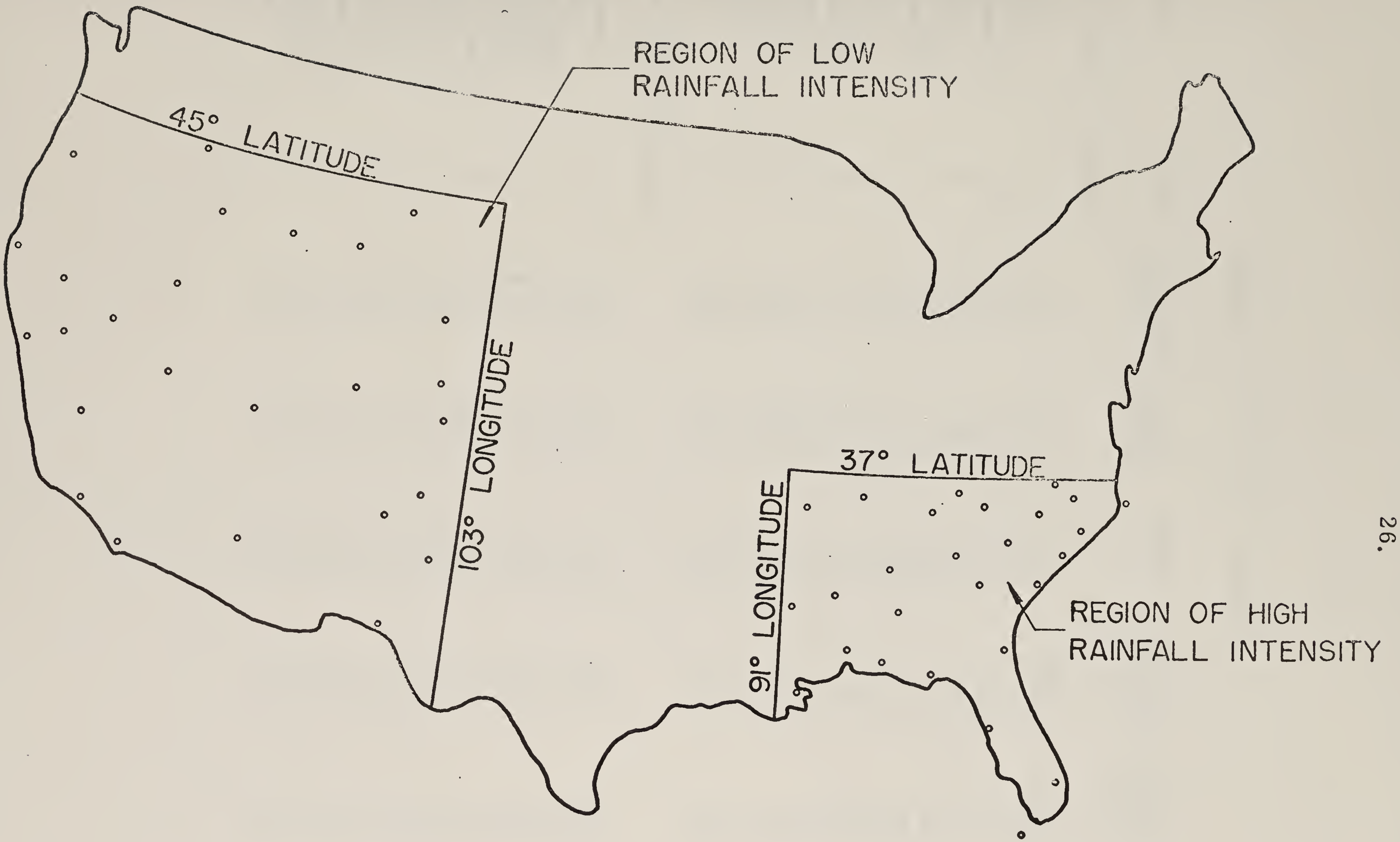
REGION OF LOW RAINFALL INTENSITY
45° LATITUDE
103° LONGITUDE
37° LATITUDE
91° LONGITUDE
REGION OF HIGH RAINFALL INTENSITY

FIGURE 7 Regions of U.S.A. selected for station-year analysis. The dots represent all stations with more than 30 years of records.

TABLE 3 STATION-YEAR ANALYSIS

Station	Rank	10yr 1hr value	Max 1hr value	Ratio	Return Period Record Series	Partial Series	Year of Occurrence
LOW INTENSITY REGION							
		ins	ins		years	years	
El Paso	1	1.40	4.80	3.43	1498	1470	1881
Pueblo	2	1.60	3.41	2.13	749	722	1957
Sacramento	3	0.82	1.65	2.01	499	472	1935
Lander	4	0.80	1.45	1.81	374	347	1958
Winnemucca	5	0.61	1.10	1.80	300	272	1958
Cheyenne	6	1.45	2.51	1.74	250	222	1926
Boise	7	0.58	0.98	1.69	214	184	1912
Red Bluff	8	1.30	2.14	1.65	187	160	1918
Roseburg	9	0.72	1.16	1.61	166	136	1910
Denver	10	1.45	2.20	1.52	150	118	1921
Tonopah	11	0.58	0.86	1.48	136	104	1945
Baker	12	0.62	0.89	1.43	125	93	1908
Eureka	13	0.85	1.20	1.41	115	83	1950
Elko	14	0.68	0.94	1.38	107	76	1950
HIGH INTENSITY REGION							
Hatteras	1	3.00	5.35	1.79	1587	1558	1928
Macon	2	2.70	4.28	1.59	793	760	1923
Birmingham	3	2.50	3.83	1.54	529	500	1941
Montgomery	4	2.74	4.16	1.53	397	367	1961
Knoxville	5	2.30	3.52	1.53	317	287	1939
New Orleans	6	3.20	4.71	1.48	265	234	1953
Memphis	7	2.20	3.25	1.48	227	197	1929
Greenville	8	2.50	3.63	1.46	198	168	1951
Key West	9	3.00	4.30	1.44	176	146	1926
Ashville	10	1.90	2.70	1.42	159	127	1911
Thomasville	11	3.00	4.15	1.39	144	112	1909
Vicksburg	12	2.50	3.44	1.50	132	100	1960
Anniston	13	2.70	3.62	1.35	122	90	1906
Miami	14	3.40	4.53	1.34	113	81	1933

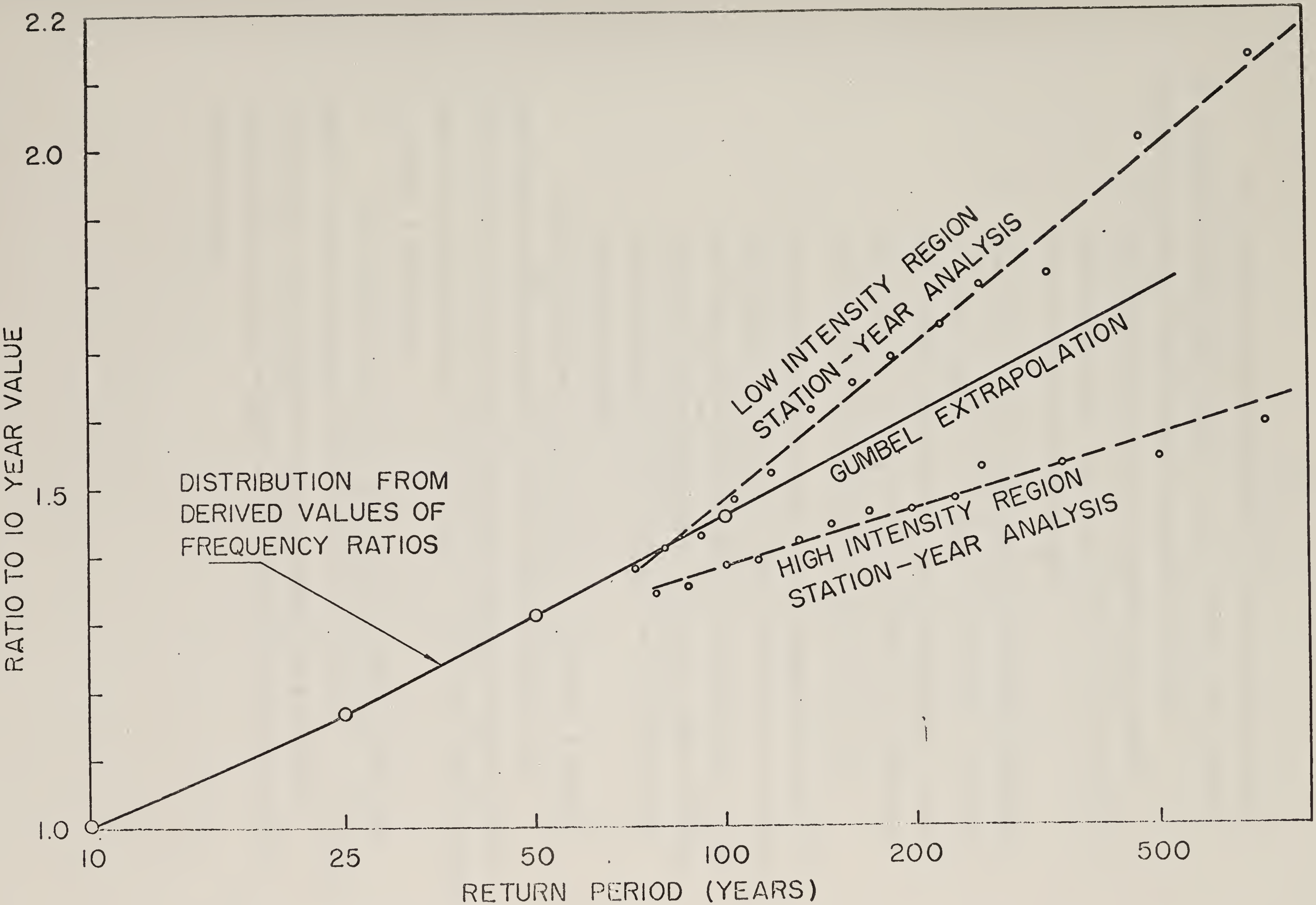

FIGURE 8 Comparison between frequency distributions derived directly from records and by station-year analysis. A Gumbel scale has been used.

The results have been plotted to a Gumbel scale in Figure 8, together with the depth-frequency ratios derived earlier from individual records. The following conclusions are made:

(a) The ratios derived from the station-year method converge towards, and consequently verify, the ratios derived from individual records.

(b) The ratios are not independent of the rainfall magnitude for return periods exceeding about 70 years. This was also observed with the 100 year ratio derived from individual records, although there is little error in ignoring the effect for return periods of 100 years or less.

(c) The depth-frequency ratios conform approximately with the Gumbel distribution for return periods up to 100 years but if this distribution is used for extrapolations to more extreme events the estimates will be too high in regions of high intensity rainfall and too low in regions of low intensity rainfall.

The main purpose of this analysis is to provide a largely independent verification of the 100 year depth-frequency ratio. With suitable groupings of stations similar analyses could be used for more thorough derivations of very extreme rainfall with return periods exceeding 1,000 years.

The results of the entire study may be combined into one general duration-frequency function as shown in Figure 9. The implied relationships could possibly be valid throughout the world where extreme short duration rainfall is due primarily to local convective storm activity.

CONCLUSIONS

As suggested from physical considerations, extreme rainfall of short duration has distinctive characteristics that would not be expected in long duration rainfall. An appropriate method of expressing these characteristics is the conversion of the rainfall values to depth-duration and depth-frequency ratios with the 10 year 1 hour value as denominator. This procedure is more satisfactory than using the 1 year 1 hour or 2 year 1 hour value as denominator, as adopted in previous studies.

There is a particular ratio corresponding to any given duration of 2 hours or less and any return period of 100 years or less. These ratios are conveniently specified by the general duration-frequency function of Figure 9 which applies not only to the United States but also to other parts of the world.

The results of this study can expedite the derivation and presentation of rainfall frequency data in countries where it is urgently needed but not yet available. If a few typical records varify the validity of the general duration-frequency function for the area concerned, the efforts can be economically confined to the derivation of the basic 10 year 1 hour value. Where no suitable records are available for the direct determination of the 10 year 1 hour value, the methods developed by Hershfield and others[4, 5] may be used for estimates of the 2 year 1 hour value. When this is multiplied by 1.6 it should provide a reasonable estimate of the 10 year 1 hour rainfall.

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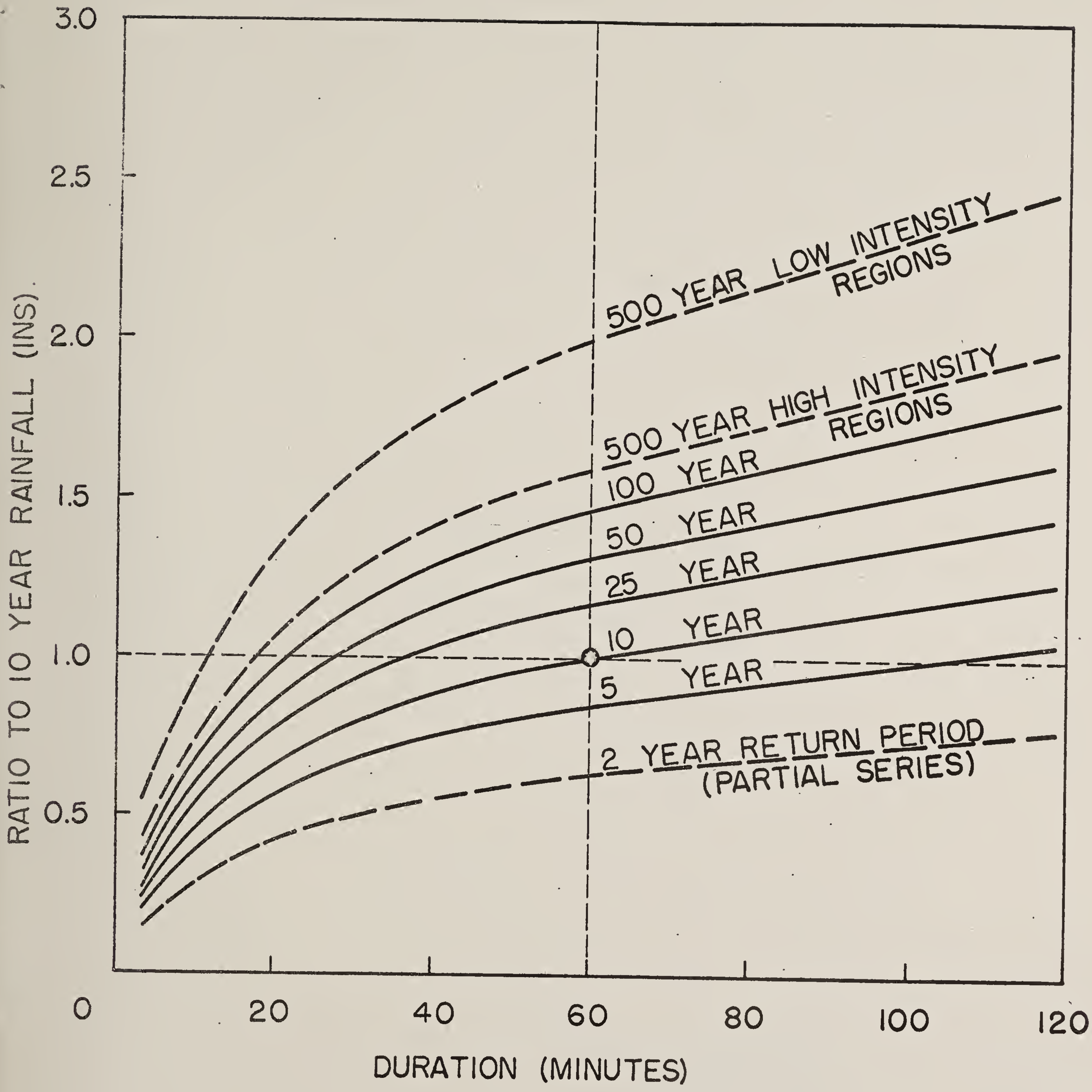

FIGURE 9 General duration-frequency function for extreme rainfall.

FIG. 9

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